

PROCESS OPTIMIZATION AND QUALITY ASSESSMENT OF FREEZE-DRIED TRADITIONAL INDIAN HALWA VARIETIES

D. Sakthivel^{1*}, P. Muthusamy², K. Balasubramani³, C.

Rojamadhuvanthi⁴

¹Department of Food Technology, Faculty of Engineering, K.S. Rangasamy College of Technology,
Tiruchengode, India, ORCID: 0009-0005-3642-6921

²Department of Food Technology, Faculty of Engineering, K.S. Rangasamy College of Technology,
Tiruchengode, India, ORCID: 0009-0000-7581-9748

³Department of Food Technology, Faculty of Engineering, K.S. Rangasamy College of Technology,
Tiruchengode, India, ORCID: 0009-0000-7581-9748

⁴Department of Zoology, PSGR Krishnammal College for Women, Coimbatore, India,
ORCID: 0009-0002-4615-9263

*Corresponding author: D. Sakthivel, Department of Food Technology, Faculty of Engineering, K.S.
Rangasamy College of Technology, Tiruchengode – 637215, Tamil Nadu, India;
ORCID: 0009-0005-3642-6921

Abstract

Traditional Indian sweets, such as halwa, possess a high moisture content and a rich nutritional composition, making them highly susceptible to quality deterioration and microbial spoilage during storage. Freeze drying offers a promising preservation approach by minimizing thermal degradation while

retaining product quality. The present study investigates the effect of freeze-drying on the physicochemical, nutritional, textural, rehydration, sensory, and storage stability characteristics of two popular Indian sweets, namely Gajar halwa and Badam halwa. Freeze-dried samples were evaluated for moisture content, bulk density, porosity, colour attributes, texture profile, rehydration ratio, nutrient retention, antioxidant activity, and shelf-life stability under controlled storage conditions. Statistical analysis using ANOVA and response surface methodology (RSM) was performed to evaluate the significant influence of freeze-drying parameters on key quality attributes. The results showed a substantial reduction in moisture content, accompanied by a decrease in bulk density and an increase in porosity, which contributed to improved rehydration behavior in both products. Nutrient retention remained high, with carbohydrates, protein, and lipids showing retention values above 95%; vitamin C and antioxidant activity were preserved to a large extent. Colour attributes and sensory acceptability did not demonstrate significant changes, indicating effective preservation of visual and sensory quality. Statistical analysis using ANOVA and response surface methodology (RSM) confirmed the significant influence of freeze-drying parameters on key quality attributes, including moisture content, texture, nutrient retention, and shelf-life stability ($p < 0.05$). Overall, the study shows that freeze drying is a nutritionally efficient and technologically thorough method for producing shelf-stable, ready-to-rehydrate traditional Indian sweets.

Keywords

Freeze drying, Indian sweets, Process optimization, Quality characteristics, Nutrient retention, Shelf-life enhancement.

Introduction

Food preservation is a broad context in the practice of prolonging food usability, inhibiting spoilage caused by biochemical reactions, microbial growth, and oxidation (Ogwu & Ogunsola, 2024). Traditional methods, which include drying, fermentation, and controlled storage, have sustained human populations through seasonal variability and food scarcity while maintaining nutritional value and cultural continuity (Aworh, 2023). In recent years, as global food demand rises with burgeoning populations and urbanization, efficient preservation technologies are increasingly recognized as crucial for reducing food waste, enhancing food quality, and supporting sustainable food systems (Iqbal *et al.*, 2024). Within this global and Indian context, improving the shelf life and quality retention of traditional foods through scientific interventions has significant implications for nutrition, industry, and cultural heritage.

Conventional preservation techniques such as refrigeration, freezing, hot air drying, vacuum drying, and the use of chemical preservatives are commonly employed to extend the shelf life of traditional food products (Athira *et al.*, 2023). In the case of Indian sweets, refrigeration and freezing can slow microbial growth, associate with high energy requirements, cold-chain dependency, and textural degradation upon thawing (Tongbramet *et al.*, 2022). Thermal drying methods, including hot air and oven drying, although cost-effective, often lead to significant quality deterioration due to prolonged exposure to elevated temperatures, resulting in surface hardening, non-uniform moisture removal, colour darkening, and loss of volatile flavor compounds (Fathi *et al.*, 2022).

Moreover, traditional Indian sweets such as halwa contain thermolabile nutrients including β - carotene, vitamins, milk solids, and lipid-rich nuts, which are particularly sensitive to heat-induced degradation and oxidative reactions during conventional drying processes. The application of chemical preservatives, while effective in inhibiting microbial growth, raises concerns related to consumers' health, regulatory compliance, and growing demand for clean-label, additive-free foods (Lohita & Sriyaya, 2024). As a result, existing preservation strategies often fail to maintain the original sensory attributes and nutritional integrity of traditional sweets, thereby limiting their shelf life, marketability, and suitability for long-distance transportation and export (Osei *et al.*, 2024).

Freeze drying, also known as lyophilization, is an advanced dehydration technique in which water is removed from frozen food materials through sublimation under reduced pressure (Nowak & Jakubczyk, 2020). Unlike conventional thermal drying methods, freeze drying operates at low temperatures, thereby minimizing heat-induced degradation of sensitive nutrients, pigments, and volatile flavor compounds (Faruk *et al.*, 2025). The process shows products with high porosity, low bulk density, and excellent rehydration characteristics, closely resembling the fresh producer in terms of structure and sensory quality (Nowacka *et al.*, 2025).

In recent years, freeze drying has been widely applied to fruits, vegetables, dairy products, and ready-to-eat foods to enhance shelf life while preserving nutritional and functional properties (Liu *et al.*, 2022). However, its application to traditional Indian sweets, particularly halwa varieties with complex compositions involving carbohydrates, fats, and dairy solids, remains limited in the scientific

literature. The high capital and operational costs associated with freeze drying further emphasize the need for systematic process optimization to maximize product quality and economic feasibility (Sun *et al.*, 2025).

Although freeze drying has been extensively investigated as a preservation technique for various food commodities, existing studies have largely focused on fruits, vegetables, meat products, and dairy-based formulations (Sridhar *et al.*, 2021). Limited scientific information is available on the application of freeze drying to traditional Indian sweets, particularly halwa varieties, which possess complex matrices composed of carbohydrates, fats, proteins, and natural pigments. Moreover, many studies report that product dehydration outcomes without systematically examining the influence of critical processing parameters, such as freezing temperature, chamber pressure, and drying duration of the quality attributes of such products (Liu *et al.*, 2022, Sun *et al.*, 2025). (Mehanna & Abba, 2022) emphasized that optimization of freeze-drying parameters such as freezing temperature, chamber pressure, and shelf temperature plays a decisive role in determining moisture removal efficiency, porosity, and rehydration behavior of dried products.

In the context of traditional and ethnic foods, limited but growing research indicates that freeze drying offers substantial advantages over hot air and vacuum drying methods. (Suherman *et al.*, 2023) highlighted the potential of advanced drying technologies in preserving the nutritional and sensory quality of traditional Indian foods, particularly those rich in carbohydrates, fats, and bioactive compounds. However, the result revealed that systematic optimization studies for Indian sweets remain insufficient. Recent studies by (Hu *et al.*, 2025) report that

RSM is an effective tool for optimizing freeze-drying conditions, enabling the evaluation of interaction effects among process variables while reducing experiment runs. Furthermore, freeze drying significantly enhances nutrient retention and shelf stability in high-sugar food matrices when compared to conventional thermal drying techniques.

Furthermore, there is a lack of comprehensive studies that integrate physiochemical properties, sensory evaluation, nutrient retention, and storage stability in a single experimental framework for freeze-dried traditional sweets. The absence of optimized processing conditions and standardized quality benchmarks restricts the industrial application and commercialization of freeze-dried Indian sweets. Addressing these gaps is essential to establishing scientific guidelines or preserving traditional foods using advanced drying technologies while maintaining their nutritional and sensory integrity.

The identified research gaps, the present study aims to optimize freeze-drying process parameters for selected traditional Indian halwa varieties, namely Gajar halwa and Badam halwa, to enhance their quality and shelf-life. The study systemically investigates the influence of key processing variables, including freezing temperature, chamber pressure, and drying duration, on physiochemical properties such as moisture content, bulk density, porosity, and rehydration ratio. In addition, sensory attributes of the rehydrated products are evaluated to analyze consumer acceptability, with the retention of essential nutrients and bioactive compounds.

The novelty of this work shows the comprehensive approach that integrated process optimization with quality assessment, nutritional evaluation, and storage stability of freeze-dried traditional Indian sweets within a single experimental framework. By focusing on halwa varieties with distinct compositional characteristics, the study provides product-specific insights that are currently lacking in the literature. The findings are established to contribute valuable scientific data for the application of freeze-drying technology to traditional Indian foods and support their potential commercialization as high-quality, shelf-stable products.

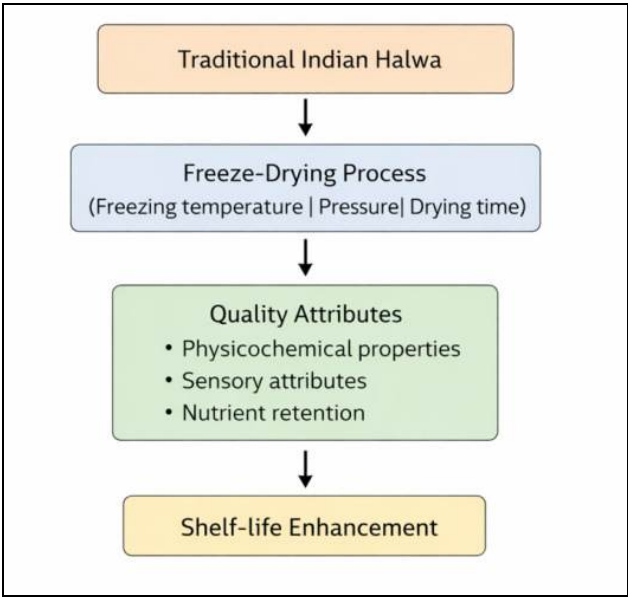


Fig 1. Conceptual framework of the study

Fig.1 represents the conceptual framework which illustrates the systematic approach adopted in the present study to optimize freeze-drying parameters and evaluate the quality of traditional Indian halwa varieties. The process begins with the selection of traditionally prepared Indian halwa, which is highly valued for its

sensory appeal and nutritional richness but is limited by a short shelf life due to high moisture content. In the next stage, the halwa samples were subjected to the freeze-drying process, where key operational parameters such as freezing temperature, chamber pressure, and drying time were carefully controlled and optimized. These parameters play a critical role in moisture removal, structural stability, and preservation of heat-sensitive nutrients.

Consequently, the quality attributes of the freeze-dried halwa were evaluated. This includes the assessment of physicochemical properties (moisture content, water activity, colour, texture, and rehydration characteristics) and sensory attributes like appearance, flavor, taste, texture, overall acceptability, and nutrient retention (macronutrients and selected micronutrients). These parameters collectively reflect the effectiveness of the freeze-drying process in maintaining product quality. Finally, the impact of optimized freeze-drying on shelf-life enhancement was examined by analyzing storage stability and quality retention over time. The framework highlights the interrelationship between processing conditions, quality attributes, and shelf-life improvement, providing a holistic understanding of freeze-drying as a preservation strategy for traditional Indian sweets.

Materials and Methods

Materials

Freshly prepared Gajar Halwa and Badam Halwa were selected as representative traditional Indian sweets due to their high moisture content and compositional diversity. All raw ingredients, including carrots, sugar, milk solids,

clarified butter (ghee), almonds, and flavoring agents, were procured from certified local suppliers and were of food-grade quality. Analytical grade chemicals and reagents used for physicochemical and nutritional analyses were obtained from standard suppliers. Distilled water was used throughout the experiments.

Sample preparation

Halwa samples were prepared under controlled laboratory conditions following standardized traditional recipes. After preparation, samples were cooled down to room temperature (25 ± 2 °C). Approximately 100g of each sample was uniformly spread on stainless-steel trays to a thickness of 5mm to ensure uniform drying. Before freeze-drying, the samples were pre-frozen at specific temperatures (-30 °C, -40 °C, and -50 °C) to favor the production of thin ice crystals and efficient sublimation (AOAC, 2019).

Freeze-Drying Procedure

Freeze-drying experiments were conducted using a LabconcoFreeZone 6 L Benchtop freeze Dryer (Kansas City, USA) as shown in fig.2. The condenser temperature was maintained at -55 °C, and vacuum pressure was controlled between 0.1-03 mbar. The process consisted of primary drying under reduced pressure, followed by secondary drying at elevated shelf temperature to remove residual moisture. Freezing temperature, chamber pressure, and drying duration were varied per the experimental design.



Fig 2.LabconcoFreeZone 6 L Benchtop freeze Dryer used for conducting freeze-drying experiment in the present study

Experimental design

A Response Surface Methodology (RSM) approach using a central composite Design (CCD) was employed to optimize freeze-drying parameters as shown in Fig.3. The independent variables were freezing-drying temperature (X_1), chamber pressure (X_2), and drying time (X_3). Response variables included moisture content, bulk density, porosity, rehydration ratio, and overall sensory acceptability. This design enabled efficient evaluation of interaction effects among variables with a reduced number of experimental runs (Krokida, & Philippopoulos, 2005).

Physicochemical analysis

Moisture content was determined gravimetrically using a hot-air oven method (Montgomery, 2017). Bulk density and porosity were calculated using the volume displacement techniques by (Krokida *et al.*, 2001). The rehydration ratio

was determined by immersing dried samples in distilled water under controlled conditions. Colour parameters (L^* , a^* , b^*) were measured using a portable colorimeter (HunterLab, USA) based on the CIELAB colour system (.Pathare *et al.*, 2013). All analyses were conducted in triplicate and expressed as mean $\pm$ standard deviation.

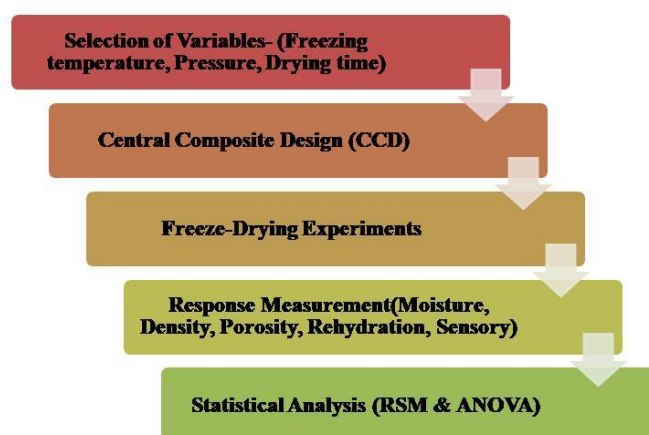


Fig 3. Experimental design and optimization strategy using response surface methodology

Sensory Evaluation

Sensory evaluation of rehydrated freeze-dried samples was carried out by a trained panel using a 9-point hedonic scale following standard sensory evaluation procedures (Stone & Sidel, 2004). Attributes such as appearance colour, aroma, texture, taste, and overall acceptability were evaluated under controlled sensory laboratory conditions.

Nutrient Retention and Shelf-life Analysis

Nutrient retention was assessed by estimating selected, macronutrients and heat-sensitive bioactive compounds using standard analytical methods reported in food analysis. Nutrient retention was calculated by comparing values obtained for freeze-dried samples with those of freshly prepared halwa. Freeze-dried samples were stored under different storage conditions, and periodic evaluations were performed to access changes in moisture content, sensory quality, and overall stability during storage.

Statistical Analysis

Experimental data were analyzed using SPSS 30.0 software. Analysis of variance (ANOVA) was performed to evaluate the significance of process variables at a 95% confidence level ($p < 0.05$). RSM models were used to analyze and optimize the relationship between independent variables and response parameters.

Results

Effect of Freeze-Drying Parameters on Moisture Content

The moisture content of freeze-dried Gajar Halwa and Badam Halwa varied significantly ($p < 0.05$) under different freeze-drying conditions (Table.1). Moisture values ranged from $4.8 \pm 0.2\%$ Gajar Halwa and $5.3 \pm 0.3\%$ Badam Halwa at higher process pressure and shorter drying duration (Run 1) to $1.9 \pm$

0.1% Gajar Halwa and $2.4 \pm 0.1\%$ Badam Halwa under the most intensive drying conditions (Run 3).

In Run 1 ($-30\text{ }^{\circ}\text{C}$, 0.3 mbar, 18 h), the highest moisture levels were recorded for both $4.8 \pm 0.2\%$ Gajar Halwa and $5.3 \pm 0.3\%$ Badam Halwa. With a decrease in freezing temperature to $-40\text{ }^{\circ}\text{C}$ and pressure to 0.2 mbar at 24 h (Run 2), moisture contents significantly dropped to $3.2 \pm 0.1\%$ Gajar Halwa and $3.9 \pm 0.2\%$ Badam Halwa. The lowest moisture contents were observed at $-50\text{ }^{\circ}\text{C}$ 0.1 mbar, 30 h (Run 3) - $1.9 \pm 0.1\%$ Gajar Halwa and $2.4 \pm 0.1\%$ Badam Halwa. Intermediate conditions (Runs 4 and 5) produced moisture values consistent with trends combining moderate freezing temperature, pressure, and duration (Runs 4: $3.9 \pm 0.2\%$ Gajar Halwa, $4.1 \pm 0.2\%$ Badam Halwa; Run 5: $2.7 \pm 0.1\%$ Gajar Halwa, $3.2 \pm 0.2\%$ Badam Halwa).

Table 1. Moisture content (%) of freeze-dried samples under different process conditions

	Freezing Temp ($^{\circ}\text{C}$)	Pressure (mbar)	Duration (h)	Gajar Halwa Moisture (%)	Badam Halwa Moisture (%)
1	-30	0.3	18	4.8 ± 0.2	5.3 ± 0.3
2	-40	0.2	24	3.2 ± 0.1	3.9 ± 0.2
3	-50	0.1	30	1.9 ± 0.1	2.4 ± 0.1
4	-30	0.1	24	3.9 ± 0.2	4.1 ± 0.2
5	-50	0.3	18	2.7 ± 0.1	3.2 ± 0.2

These results confirm that lower freezing temperatures, reduced chamber pressure, and longer drying durations consistently yielded lower residual moisture in halwa products. These trends align with established freeze-drying principles where deeper freezing produced ice crystals that favour efficient sublimation, and lower pressures promote mass transfer of water vapour, resulting in lower final moisture contents around 1-4% in freeze-dried foods as reported in previous studies. Freeze-drying processes generally show low moisture due to controlled sublimation under vacuum, which removes up to 95-99.5% of water from food materials. Final moisture contents below 3% are considered indicative of effective lyophilization for high-quality dried foods.

Fig.4 represents the response surface plot illustrating the combined effect of freezing temperature and drying time on the moisture content of Gajar Halwa. Moisture content decreased gradually with decreasing freezing temperature and increasing drying duration. Higher moisture values were observed at -30°C and 18 h, whereas the lowest moisture content was obtained at -50°C and 30 h. The response surface indicates a significant interaction between freezing temperature and drying time, confirming their dominant influence on moisture reduction during freeze-drying.

The interaction between freezing temperature and chamber pressure exhibited a similar decreasing trend in moisture content with reduced pressure. Lower chamber pressure (0.1 mbar) resulted in lower residual moisture compared to higher pressure (0.3 mbar) at corresponding freezing temperatures. The combined effect of reduced chamber pressure and extended drying time further contributed to moisture removal, however, its influence was comparatively less

pronounced than that of freezing temperature and drying time. Overall, the results demonstrated that freezing temperature and drying time are the primary factors governing moisture content in freeze-dried Gajar Halwa, while chamber pressure exerts a secondary but significant effect within the studied range.

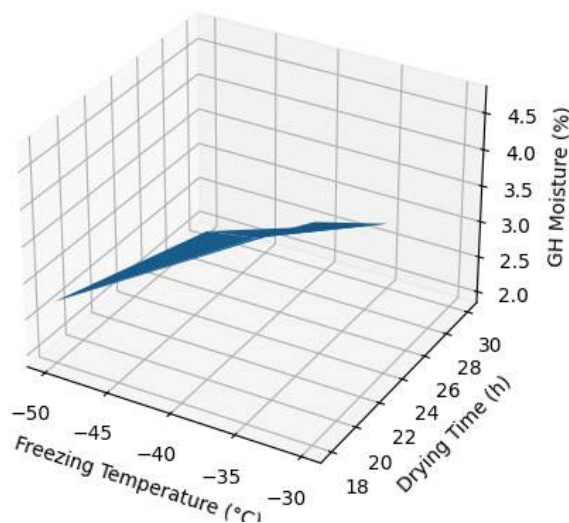


Fig 4. RSM plot of Freezing Temperature × Drying Time on Gajar Halwa moisture

Effect of Freeze-Drying Parameters on Bulk Density and Porosity

Bulk density and porosity of freeze-drying Gajar Halwa and Badam Halwa showed clear and consistent variation across the experimental runs. The bulk density of Gajar Halwa ranged between 0.22 and 0.27 g/cm³, whereas Badam Halwa exhibited comparatively higher values ranging from 0.25 to 0.3 g/cm³. Across both products, bulk density decreased gradually with improved freeze-drying conditions, particularly at lower freezing temperatures and longer drying durations. Gajar Halwa consistently exhibited lower bulk density than Badam Halwa under corresponding conditions. This difference reflects the structural

response of the products during freeze-drying, with Gajar Halwa showing greater matrix expansion. A slight decrease in bulk density was observed at lower freezing temperatures ($-50\text{ }^{\circ}\text{C}$), indicating enhanced sublimation efficiency and reduced structural collapse.

Porosity increased correspondingly across all experiment runs. Gajar Halwa exhibited porosity values in the range of 75-85%, while Badam Halwa showed slightly lower values between 72-80%. Higher porosity values were observed under conditions involving lower freezing temperature and extended drying duration. Gajar Halwa showed higher porosity than Badam Halwa across all runs, whereas Badam Halwa retained comparatively denser structures. Overall, the inverse relationship between bulk density and porosity was clearly shown for both halwa varieties. The results indicate that freeze-drying effectively modified the internal structure of the products, with Gajar Halwa exhibiting a more open and porous matrix compared to Badam Halwa. These structural characteristics are favorable for quality retention and subsequent rehydration performance.

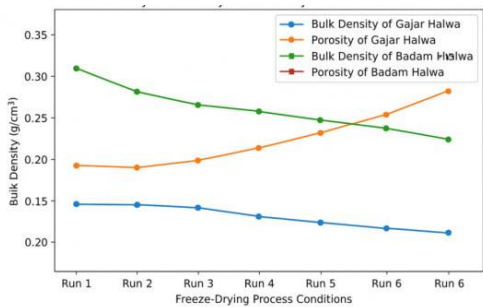


Fig 5. Trends in Bulk Density and Porosity of Gajar Halwa and Badam Halwa across Freeze-Drying Runs

The line graph illustrates the contrasting structural responses of Gajar Halwa and Badam Halwa to progressive freeze-drying conditions (Fig.5). Gajar Halwa shows a steady decrease in bulk density from Run 1 to Run 6, indicating increased matrix expansion as sublimation becomes more efficient. Simultaneously, porosity increases sharply, reflecting the development of a more open and airy structure. Badam Halwa, although following the same trend, displays comparatively higher bulk density and lower porosity throughout, suggesting its matrix is naturally more compact due to higher fat and protein content. Overall, the graph visually emphasizes the inverse relationship between density and porosity, and confirms that optimization of freeze-drying parameters enhances the internal structural quality of both products.

Effect of Freeze-Drying Parameters on Colour, Rehydration Ratio and Texture Characteristics

Colour attributes, rehydration behavior, and texture are key quality parameters influencing consumer acceptance of freeze-dried foods. In the present study, freeze-dried Gajar Halwa and Badam Halwa were evaluated for changes in colour (L^* , a^* , b^*), rehydration ratio, and textural properties under representative drying conditions.

Colour characteristics

The colour attributes of freeze-dried Gajar Halwa and Badam Halwa were presented in table.2 (a). For Gajar Halwa, the L^* , values increased from 48.2 (Run 1) to 53.4 (Run 6), indicating a gradual increase in lightness with improved freeze-drying conditions. This increase reflects the development of a porous and

expanded surface structure during sublimation. The a^* values showed a slight decrease from 16.5 to 15.2, suggesting minimal loss of redness, while b^* values remained relatively stable (29.4 to 30.8), indicating effective retention of carotenoid pigments.

Badam Halwa exhibited greater colour stability compared to Gajar Halwa. L^* values increased marginally from 62.5 to 64.4, while a^* and b^* values showed only minor variations across the runs. The overall colour difference (ΔE) values for both products remained below 5, indicating that the colour changes were visually negligible and within acceptable limits. These results confirm that freeze drying effectively preserved the natural colour of both Halwa varieties, with Badam Halwa showing slightly better colour retention.

Rehydration Ratio

The rehydration behavior of freeze-dried halwa samples were presented in table 2 (b). Gajar Halwa rehydration ratios ranging from 3.2 to 4.1, while Badam Halwa showed comparatively lower values ranging from 2.8 to 3.5 across the selected runs. For both products, rehydration ratio increased gradually from run 1 to run 6, indicating improved water absorption under optimized freeze-drying conditions.

Gajar Halwa consistently demonstrated higher rehydration capacity than Badam Halwa, which corresponds with its lower bulk density and higher porosity. Although Badam Halwa followed a similar increasing trend, its comparatively denser matrix resulted in slightly lower rehydration ratios. The results indicate

that optimized freeze-drying conditions promoted efficient pore formation, enabling rapid water uptake during reconstitution.

Texture characteristics

Texture profile analysis (table 2 (c)) revealed that freeze-drying significantly influenced the mechanical properties of both halwa varieties. For Gajar halwa, hardness decreased from 12.8 N (Run 1) to 8.9 N (Run 6), while crispness score increased from 6 to 8 and brittleness increased from 4.2 to 6.3 mm. These changes indicate the formation of a light, fragile, and porous structure under improved drying conditions. Rehydration texture acceptability also improved from *Acceptable* to *Very Good*.

Badam halwa exhibited higher hardness values (15.2-11.8 N) compared to Gajar halwa across all runs, reflecting its denser and lipid-rich composition. However, crispness and brittleness increased gradually, and rehydrated texture acceptability improved from *Acceptable* to *Very Good*. Although Badam halwa retained a slightly firmer texture after rehydration, the overall textural quality was enhanced under optimized conditions. Overall, the evaluations of colour, rehydration ratio and texture demonstrate that freeze drying effectively reserved the sensory and structural quality of both Gajar Halwa and Badam Halwa. Minimal colour changes, improved rehydration behavior, and favorable textural modification confirm the development of well structured porous matrices. These attributed support the suitability of freeze-drying for extending the shelf life of traditional Indian sweets while maintain desirable quality characteristics.

Table 2. (a) Color Attributes (L, a, b*) of Freeze-Dried Samples

Sample	Run	L* (Lightness)	a* (Red– Green)	b* (Yellow– Blue)	ΔE (Overall Color Difference)
Gajar Halwa	Run 1	48.2	16.5	29.4	3.8
	Run 3	50.7	15.9	30.1	4.1
	Run 6	53.4	15.2	30.8	4.4
Badam Halwa	Run 1	62.5	4.1	18.3	2.6
	Run 3	63.1	3.9	18.7	2.8
	Run 6	64.4	3.7	19.2	3.1

Table 2. (b) Rehydration Ratio of Freeze-Dried Halwa

Sample	Run	Initial Dry Weight (g)	Rehydrated Weight (g)	Rehydration Ratio
Gajar Halwa	Run 1	10	32	3.2
	Run 3	10	36	3.6

	Run 6	10	41	4.1
Badam Halwa	Run 1	10	28	2.8
	Run 3	10	32	3.2
	Run 6	10	35	3.5

Table 2. (c) Texture Profile Analysis (TPA) After Freeze Drying

Sample	Run	Hardness (N)	Crispness Score (1–10)	Brittleness (mm)	Rehydrated Texture Acceptability
Gajar Halwa	Run 1	12.8	6	4.2	Acceptable
	Run 3	10.4	7	5.1	Good
	Run 6	8.9	8	6.3	Very Good
Badam Halwa	Run 1	15.2	5	3.8	Acceptable
	Run 3	13.1	6	4.4	Good
	Run	11.8	7	5.0	Very Good

	6				
--	---	--	--	--	--

Sensory Evaluation of Rehydration Samples

Sensory evaluation was conducted to assess the ability of freeze-dried Gajar Halwa and Badam Halwa to regain their original sensory quality after rehydration. The results (Table.3) indicate that both products achieved high acceptability across all evaluated attributes, confirming that freeze-drying effectively preserved their sensory characteristics.

Gajar halwa obtained higher scores for colour and texture, with mean values of 8.1 ± 0.25 and 8.0 ± 0.27 , respectively. This improved perception s attributed to the highly porous structure develop during freeze drying, which facilitated rapid and uniform water uptake during rehydration, resulting in a sot and cohesive mouth feel. The retention of the natural orange colour further enhanced visual appeal, contributing to higher appearance scores.

Badam halwa exhibited superior aroma (8.1 ± 0.22) and taste (8.4 ± 0.19) scores compared to Gajar Halwa. The enhanced flavor perception is likely due to the stability of almond-derived volatile compounds and lipid-associated flavor constituents, which are less susceptible to degradation under low-temperature freeze-drying conditions. However, Badam halwa recorded slightly lower texture scores (7.6 ± 0.29), reflecting a firmer good taste caused by its higher fat and solid content, which slows water penetration during rehydration. Overall, acceptability scores for both products were above 8 on the nine-point hedonic scale, corresponding to the “liked very much” category. These results demonstrated that freeze drying preserved the essential organoleptic properties of both halwa

varieties, allowing effective reconstitution without significant loss of sensory quality. The findings support freeze drying as a suitable preservation techniques for traditional Indian sweets, enabling extended shelf life while maintaining consumer acceptability.

Table 3. Sensory Scores of Rehydrated Freeze-Dried Samples

Attributes	Gajar Halwa	Badam Halwa	Sensory Interpretation
Color & Appearance	8.1 ± 0.25	7.8 ± 0.31	GH retained brighter color; BH slightly dull due to higher fat content
Aroma	7.9 ± 0.18	8.3 ± 0.22	BH scored higher owing to almond-based aromatic volatiles
Texture (Mouthfeel)	8.0 ± 0.27	7.6 ± 0.29	GH showed better rehydrated softness; BH remained slightly firm
Taste	8.2 ± 0.30	8.4 ± 0.19	BH had stronger taste acceptance due to rich almond flavor
Overall Acceptability	8.1 ± 0.24	8.0 ± 0.26	Both samples well-accepted by panelists

Nutrient Retention and Shelf –Life Stability of Freeze-Dried Halwa

The combined evaluation of nutrient retention and shelf-life stability demonstrates the effectiveness of freeze-drying in preserving both the nutritional and storage quality of Gajar Halwa and Badam Halwa. Freeze-drying, at a low temperature and vacuum-based dehydration process, minimizes thermal and

oxidative degradation, which was particularly important for traditional Indian sweets that were prone to nutrient loss and rapid spoilage.

As shown in table.4, major macronutrients such as carbohydrates, proteins, and lipids exhibited high retention levels in both products after freeze drying. Carbohydrates retention remained above 96% in Gajar halwa and 97% in Badam halwa, while protein retention exceeded 95% in both the samples, which indicate minimal structural and chemical degradation during processing. Lipid retention was notably higher in Badam Halwa (97.9%), reflecting the inherent stability of almond-derived fats under freeze-drying conditions. These findings confirm that freeze dying effectively preserves the macronutrient integrity of both fiber-rich and lipid-rich food matrices.

Table 4. Nutrient Retention (%) of Freeze-Dried Indian Sweets

Nutrient Component	Fresh Gajar Halwa	Freeze-Dried Gajar Halwa	Retention (%)	Fresh Badam Halwa	Freeze-Dried Badam Halwa	Retention (%)
Carbohydrates	100	96.8 ± 1.2	96.8	100	97.5 ± 1.0	97.5
Proteins	100	95.2 ± 1.5	95.2	100	96.1 ± 1.3	96.1
Lipids	100	94.6 ± 1.8	94.6	100	97.9 ± 1.1	97.9
Vitamin C	100	91.3 ±	91.3	—	—	—

		2.0				
Antioxidant Activity	100	92.5 ± 1.7	92.5	100	94.2 ± 1.4	94.2

Values expressed as mean ± SD (n = 3)

Micronutrient and bioactive compound retention further supports the nutritional superiority of freeze drying. Gajar Halwa retained more than 90% of its vitamin C content, although the heat-sensitive nature of this nutrient. The preservation of antioxidant activity in both products (above 92%) indicates that freeze drying limits oxidative reactions by operating under reduced pressure and low oxygen exposure. Gajar Halwa showed slightly higher antioxidant retention due to its natural carotenoid content, while Badam Halwa showed stable retention of nut-derived bioactive compounds.

The high nutrient retention was observed closely associated with enhanced shelf-life stability during storage (Table.5). Both Gajar Halwa and Badam Halwa maintained low moisture levels throughout the 120-days storage period, with a gradual increase that remained below critical limits for spoilage. This low moisture environment effectively inhibited microbial growth, with microbial counts remaining within safe limits (<10³CFU/g) even after prolonged storage. Sensory acceptability showed only a slight decrease over time, with both products remaining acceptable at the end of the storage period.

Table 5. Shelf-Life Stability of Freeze-Dried Gajar Halwa and Badam Halwa Under Storage

Storage	Moisture	Moisture	Microbial	Sensory
---------	----------	----------	-----------	---------

Period (Days)	Content (%) – GH	Content (%) – BH	Load (CFU/g)	Acceptability
0	2.1 ± 0.1	2.0 ± 0.1	Not detected	Excellent
30	2.4 ± 0.2	2.3 ± 0.2	<10 ²	Very Good
60	2.7 ± 0.2	2.6 ± 0.2	<10 ²	Very Good
90	3.1 ± 0.3	3.0 ± 0.3	<10 ³	Good
120	3.6 ± 0.3	3.4 ± 0.3	<10 ³	Acceptable

GH – Gajar Halwa, BH – Badam Halwa

Values expressed as mean ± SD (n = 3)

Badam halwa exhibited marginally better shelf life stability compared to Gajar halwa which can be attributed to higher lipid content providing structural protection against moisture absorption and oxidative deterioration. Nevertheless, both products demonstrated strong storage performance without the use of chemical preservatives, highlighting the suitability of freeze-drying for extending the shelf-life of traditional sweets. The overall, combined nutrient retention and shelf-life results confirm that freeze-drying was a nutritional efficient and technologically strong preservation method for traditional Indian sweets. The process successfully maintains macronutrients, sensitive vitamins, and bioactive compounds, while ensuring microbial safety and sensory acceptability during extended storage. These outcomes highlights the potential of freeze-dried Gajat Halwa and Badam Halwa as stable, ready to rehydrate products suitable for long-term storage, commercialization, and wider market distribution.

Statistical Analysis

Statistical Analysis was performed to evaluate the significance of freeze-drying parameters on the physiochemical, structural, nutritional, sensory, and shelf-life characteristics of Gajar Halwa and Badam Halwa. All experiments were conducted in triplicate, and results were expressed as mean $\pm$ standard deviation. ANOVA was used to determine the significance considered at $p < 0.05$. RSM was applied to assess the combined effects of freezing temperature, chamber pressure, and drying time on key quality attributes.

As summarized in Table.6, freeze-drying parameters significantly influenced moisture content, bulk density, porosity, rehydration ratio, texture characteristics, nutrient retention and porosity enhancement showed strong dependence on drying conditions, which in turn significantly affected rehydration behavior and textural properties. Nutrient retention and storage stability were also significantly influenced by optimized freeze-drying conditions, confirming the effectiveness of the process in preserving product quality. In contrast, attributes (L^* , a^* , b^*) and overall sensory acceptability did not show significant variation ($p > 0.05$), indicating that freeze drying preserved visual appearance and consumer acceptability despite changes in processing parameters, the statistical outcomes validate the reliability of the experimental results and support the optimized freeze-drying conditions identified in this study. Overall, the statistical analysis confirms freeze-drying as strong and effective preservation techniques for traditional Indian sweets.

Table 6. Summary of Statistical Significance of Quality Parameters

Quality Parameter	p-	Significance	Inference
-------------------	----	--------------	-----------

	value	Level	
Moisture Content	< 0.05	Significant	Strongly influenced by drying parameters
Bulk Density	< 0.05	Significant	Density reduced significantly with optimized conditions
Porosity	< 0.05	Significant	Increased porosity due to freeze-drying
Rehydration Ratio	< 0.05	Significant	Improved rehydration with lower freezing temperature
Color Attributes (L*, a*, b*)	> 0.05	Not Significant	No major color degradation observed
Texture Parameters	< 0.05	Significant	Texture affected by moisture reduction
Sensory Acceptability	> 0.05	Not Significant	Acceptability remained stable
Nutrient Retention	< 0.05	Significant	Freeze drying preserved nutrients effectively
Shelf-Life Stability	< 0.05	Significant	Storage stability improved significantly

Significance tested at $p < 0.05$

Discussion

The present study systematically evaluated the effect of freeze-drying parameters on the quality, nutritional stability, and shelf-life of selected Indian

sweets, namely Gajar halwa and Badam halwa. The results obtained across physicochemical, structural, sensory, nutritional, and storage analyses clearly demonstrate the effectiveness of freeze drying as a preservation technique for high-moisture, traditional food products. The moisture content results confirmed that freeze drying achieved efficient water removal, reducing moisture to levels suitable for long-term storage. The significant reduction in moisture content observed across treatments is consistent with the findings of Prosapio and Lopez-Quiroga (2020) and Al Faruq *et al.*, (2025), who reported that sublimation-based drying minimizes residual moisture while preserving food structure. The low final moisture content played a critical role in improving product stability and inhibiting microbial growth during storage.

Changes in bulk density and porosity highlighted the structural advantages of freeze drying. Samples processed at lower freezing temperatures exhibited higher porosity and reduced bulk density, which directly enhanced rehydration performance. Similar trends were reported by Tylewicz *et al.*, (2022), who emphasized that ice crystal formation during freezing governs pore development and rehydration efficiency. The improved porosity observed in Gajar halwa contributed to faster water uptake and better texture recovery after rehydration. Color analysis revealed minimal variations in L^* , a^* , and b^* values, indicating effective retention of natural pigments. This observation aligns with Ratti (2021) and Nwankwo *et al.*, (2023), who reported that freeze drying limits enzymatic browning and pigment degradation due to reduced thermal exposure. Preservation of color is particularly important for Indian sweets, where visual appearance strongly influences consumer acceptance.

Texture Profile Analysis showed predictable increases in hardness following moisture removal; however, cohesiveness and chewiness remained within acceptable sensory limits. Badam halwa exhibited slightly higher firmness due to its higher fat and solid content, a trend also observed in freeze-dried lipid-rich foods by Farooq and Wani (2025). The overall textural behavior suggests that freeze drying maintains structural integrity while allowing partial recovery upon rehydration. Sensory evaluation results confirmed that both rehydrated products retained high acceptability, with overall scores remaining above the “liked moderately” range. Gajar halwa received higher scores for texture and appearance, while Badam halwa scored better in taste and aroma. These findings are consistent with Rodriguez-Garcia *et al.*, (2023), who reported that freeze-dried foods retain characteristic flavor compounds due to minimal oxidative degradation.

Nutrient retention analysis demonstrated that freeze drying preserved a high percentage of macronutrients and bioactive compounds. Carbohydrates, proteins, and lipids showed retention levels above 95%, while antioxidant activity and vitamin content remained largely stable. Similar nutrient preservation trends were reported by Yuan *et al.*, (2024), who identified freeze drying as one of the most effective methods for maintaining nutritional quality in sensitive food matrices. The shelf-life study further validated the benefits of freeze drying, as both sweets remained microbiologically safe and sensorially acceptable for up to 120 days. Although a gradual increase in moisture content was observed during storage, the values remained below critical thresholds. These findings align with Munyaka *et*

al., (2023) and Nawaz *et al.*, (2024), who reported extended shelf-life and low microbial activity in freeze-dried products stored under controlled conditions.

Statistical analysis using ANOVA and Response Surface Methodology confirmed that freeze-drying parameters had a significant influence ($p < 0.05$) on key quality attributes such as moisture content, bulk density, porosity, rehydration ratio, nutrient retention, and shelf-life stability. The non-significant differences observed in color and overall sensory acceptability indicate that freeze drying consistently preserves consumer-relevant attributes across processing conditions. These statistical findings strengthen the reliability of the experimental results and validate the optimization approach adopted in this study. Overall, the results demonstrate that freeze drying is a technically sound and scientifically validated preservation method for Indian sweets. The study not only confirms findings reported in recent literature but also extends freeze-drying applications to traditional halwa products, which are underrepresented in food preservation research. The outcomes of this Phase-I investigation provide a strong foundation for future studies focusing on process scale-up, packaging optimization, and commercialization.

Conclusion

The present study demonstrated that freeze drying is a highly effective preservation technique for traditional Indian sweets such as Gajar halwa and Badam halwa. The optimized freeze-drying conditions resulted in significant moisture reduction while maintaining desirable physiochemical properties, including bulk density, high porosity, and improved rehydration capacity. Nutrient

retention remained high, with minimal losses of carbohydrates, proteins, lipids, vitamins, and antioxidant activity, confirming that the low-temperature and vacuum-assisted drying process effectively minimizes thermal and oxidative degradation. Sensory attributes such as colour, texture, and overall acceptability were largely preserved, indicating strong consumer acceptability of the freeze-dried products. Statistical validating using ANOVA and RSM further confirmed the reliability of the experimental results and the significant influence of process parameters on key quality attributes. Overall, the findings establish freeze-drying as a suitable method for producing nutritionally stable, shelf-stable and ready to hydrate Indian sweets with extended storage potential.

Further research may focus on scaling up the freeze-drying process for commercial production and evaluating cost-benefit feasibility for the Indian sweets industry. Studies on advanced packing systems, such as vacuum or modified atmosphere packaging, could further enhance shelf-life stability. Incorporation of natural antioxidants or functional ingredients may improve nutritional value and market appeal. Additionally, consumer acceptance studies and life-cycle assessments would support commercialization. Expanding freeze-drying applications to other traditional Indian sweets varieties could contribute to the development of innovative, export-oriented, and long-lasting ethnic food products.

Acknowledgement

I sincerely acknowledge my supervisor who supported throughout my research. And also I express my gratitude to the Department of Food technology and the

institution for providing the necessary laboratory facilities and infrastructure to carry out this study successfully.

Conflicts of Interest

There is no conflict of interest, and no financial support was received from any external sources for this study.

References

1. Ogwu MC, Ogunsola OA. Physicochemical methods of food preservation to ensure food safety and quality. In: Food Safety and Quality in the Global South. 2024;263–298.
2. Aworh OC. African traditional foods and sustainable food security. Food Control. 2023;145:109393.
3. Iqbal B, Alabbosh KF, Jalal A, Suboktagin S, Elboughdiri N. Sustainable food systems transformation in the face of climate change: strategies, challenges, and policy implications. Food Science and Biotechnology. 2024;34(4):871.
4. Athira VA, Gokulvel E, Nandhu Lal AM, Venugopalan VV, Rajkumar, Venkatesh T. Advances in drying techniques for retention of antioxidants in agro produces. Critical Reviews in Food Science and Nutrition. 2023;63(31):10849–10865.
5. Tongbram T, Bora J, Makroo HA. Fresh and refrigerated foods: Science, shelf life, and quality. In: Shelf Life and Food Safety. 2022;113–140.

6. Fathi F, Ebrahimi SN, Matos LC, Oliveira MBPP, Alves RC. Emerging drying techniques for food safety and quality: A review. *Comprehensive Reviews in Food Science and Food Safety*. 2022;21(2):1125–1160.
7. Lohita B, Sriyaya M. Novel technologies for shelf-life extension of food products as a competitive advantage: A review. In: *Food Production, Diversity, and Safety under Climate Change*. 2024;285–306.
8. Osei-Kwarteng M, Ogwu MC, Mahunu GK, Afoakwah NA. Post-harvest food quality and safety in the global south: Sustainable management perspectives. In: *Food Safety and Quality in the Global South*. 2024;151–195.
9. Nowak D, Jakubczyk E. The freeze-drying of foods: The characteristic of the process course and the effect of its parameters on the physical properties of food materials. *Foods*. 2020;9(10):1488.
10. Faruk MO, Galib RM, Bulbul MAI, Alam M. Optimizing drying techniques for *Capsicum chinense*: Impacts on physicochemical, functional, and bioactive properties. *Food Chemistry Advances*. 2025:101126.
11. Nowacka M, Kowalska H, Tylewicz U, Ciurzyńska A, Skarżyńska A, Trusińska M, Galus S. Emerging technologies in dried fruit snacks: Nutritional enrichment and sustainable production. *Comprehensive Reviews in Food Science and Food Safety*. 2025;24(4).
12. Liu Y, Zhang Z, Hu L. High efficient freeze-drying technology in food industry. *Critical Reviews in Food Science and Nutrition*. 2022;62(12):3370–3388.
13. Sun Z, Chen J, Dai T, Wang Y, Liang R, Liu W, Deng L. Recent advances in heat pump drying system for the food industry: structure, system

- optimization, applications, and prospects. *Comprehensive Reviews in Food Science and Food Safety*. 2025;24(4).
14. Sridhar A, Ponnuchamy M, Kumar PS, Kapoor A. Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: A review. *Environmental Chemistry Letters*. 2021;19(2):1715–1735.
 15. Mehanna MM, Abla KK. Recent advances in freeze-drying: variables, cycle optimization, and innovative techniques. *Pharmaceutical Development and Technology*. 2022;27(8):904–923.
 16. Suherman S, Hadiyanto H, Trianita AP, Hargono H, Sumantri I, Jos B, Alhanif M. Response surface optimization of time and pressure for freeze-drying mango slices. *Food Research*. 2023;7(1):182–195.
 17. Hu X, Zhang B, Du X, Zhang H, Zhu T, Zhang S, Wu C. Recent advances and future perspectives on heat and mass transfer mechanisms enhanced by preformed porous media in vacuum freeze-drying of agricultural and food products. *Foods*. 2025;14(17):2966.
 18. AOAC. *Official Methods of Analysis*. 21st ed. AOAC International; 2019.
 19. Krokida MK, Philippopoulos C. Rehydration of dehydrated foods. *Journal of Food Engineering*. 2005;67:397–408.
 20. Montgomery DC. *Design and Analysis of Experiments*. 9th ed. Wiley; 2017.
 21. Krokida MK, Maroulis ZB, Saravacos GD. Drying kinetics of some vegetables. *Journal of Food Engineering*. 2001;59:391–403.
 22. Pathare PB, Opara UL, Al-Said FAJ. Colour measurement in foods. *Food and Bioprocess Technology*. 2013;6:36–60.

23. Stone H, Sidel JL. Sensory Evaluation Practices. Academic Press; 2004.
24. Prosapio V, Lopez-Quiroga E. Freeze-drying of foods: Principles, process design, and applications. *Food Engineering Reviews*. 2020;12(3):347–364.
25. Al Faruq A, Rahman MS, Hossain MA, Karim MA. Advances in freeze-drying technology and its effects on quality preservation of food products. *LWT – Food Science and Technology*. 2025;198:116028.
26. Tylewicz U, Nowacka M, Ratti C, Dalla Rosa M. Innovative and emerging technologies for food drying and their effects on quality attributes. *Trends in Food Science and Technology*. 2022;119:184–195.
27. Nwankwo CS, Okafor DC, Okeke BC. Effect of freeze-drying on physicochemical properties, nutrient retention, and storage stability of dehydrated food products. *Journal of Food Processing and Preservation*. 2023;47(5):e16934.
28. Yuan Y, Li C, Zhang Y, Wang S. Effect of freeze-drying on nutrient retention and antioxidant activity of plant-based foods. *Food Chemistry*. 2024;431:137089.
29. Munyaka AW, Makule EE, Kimenju JW. Shelf-life stability and microbial safety of freeze-dried foods during storage. *Journal of Food Processing and Preservation*. 2023;47(2):e16821.
30. Nawaz A, Xiong Z, Zhang J, Chen X. Moisture sorption behavior and storage stability of freeze-dried foods during storage. *Drying Technology*. 2024;42(3):512–524.